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A high performance hardware architecture for portable, low-power retinal vessel segmentation

Dimitris Koukounis*, Christos Ttofis, Agathoklis Papadopoulos, Theocharis Theocharides

KIOS Research Center, Department of Electrical and Computer Engineering, University of Cyprus, 75 Kallipoleos Str., P.O. Box 20537, 1678 Nicosia, Cyprus

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A B S T R A C T

The retina of the human eye and more particularly the retinal blood vasculature can be used in several medical and biometric applications. The use of retinal images in such applications however, is computationally intensive, due to the high complexity of the algorithms used to extract the vessels from the retina. In addition, the emergence of portable biometric authentication applications, as well as onsite biomedical diagnostics raises the need for real-time, power-efficient implementations of such algorithms that can also satisfy the performance and accuracy requirements of portable systems that use retinal images. In an attempt to meet those requirements, this work presents a VLSI implementation of a retina vessel segmentation system while exploring various parameters that affect the power consumption, the accuracy and performance of the system. The proposed design implements an unsupervised vessel segmentation algorithm which utilizes matched filtering with signed integers to enhance the difference between the blood vessels and the rest of the retina. The design accelerates the process of obtaining a binary map of the vessels tree by using parallel processing and efficient resource sharing, achieving real-time performance. The design has been verified on a commercial FPGA platform and exhibits significant performance improvements (up to 90 $\times$) when compared to other existing hardware and software implementations, with an overall accuracy of 92.4%. Furthermore, the low power consumption of the proposed VLSI implementation enables the proposed architecture to be used in portable systems, as it achieves an efficient balance between performance, power consumption and accuracy.

1. Introduction

Evolution in medical equipment technology led to the development of revolutionized fundus imaging systems [1]. Digital retinal images have therefore significant advantages when processed and analyzed, in performing automated diagnosis, as the retina is the only part of the human body where the blood vessels can be visualized without invasive means. To fully automate the analysis of the vessels in retinal images, the blood vessels need to be accurately located; extraction of the blood vessel tree is therefore an important and complex process that can be used to automatically monitor and diagnose diseases like diabetes and hypertension [2]. Furthermore, as the structure of the vessels in the retina is unique among individuals, it is also used in biometric authentication systems [3–5].

Several software-based attempts have been proposed, that perform retinal blood vessel extraction, and most of them target medical applications where accuracy is extremely important [6]. Many of these algorithms are able to provide satisfactory results in terms of processing performance. However, the accuracy and performance results reported by software-based approaches were achieved on state-of-the-art servers and clusters that consume excessive power, something not desirable for embedded applications. Furthermore, due to the high cost of the image capturing equipment and most importantly due to the complexity of the vessel segmentation process, the use of retinal images in identification or authentication systems was therefore rarely used [7].

Recently, a few hardware acceleration attempts have been made [8–11] to reduce the time required for vasculature segmentation, and thus make it possible to use in portable biometric or on-site medical diagnostic systems. The power and performance constraints of portable biometric authentication devices and on-site diagnostic systems impose the need for further improvements in terms of power and performance requirements. The abovementioned systems require real-time response, low resource requirements, low power consumption and, equally, accurate vessel segmentation to enable the identification/authentication of individuals, or detect changes to the structure of the

* Corresponding author.
E-mail addresses: koukounis.dimitris@ucy.ac.cy (D. Koukounis), ttofis.christos@ucy.ac.cy (C. Ttofis), papadopoulos.agathoklis@ucy.ac.cy (A. Papadopoulos), ttheocharides@ucy.ac.cy (T. Theocharides).

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vessels resulting from various diseases. Already-made hardware attempts have various insufficiencies in terms of the time needed to extract the vessel tree, and thus partially satisfy the requirements of these portable systems.

This paper therefore presents a parallel hardware architecture to accelerate retinal vessel segmentation process. The architecture is capable of segmenting the blood vasculature from the retina unsupervised, by using a matched filter approach initially proposed in [12], and which was implemented in software. The binary image generated by the proposed architecture can be used at a later stage in a segmentation-driven registration system to improve the accuracy of the registration process. The simulation results indicate that the presented retina blood vasculature segmentation hardware approach for accelerating the extraction process, exhibits high potential for portable and real-time applications, as the architecture achieves remarkable speedups relative to existing hardware ($\sim 50\times$) and software implementations ($\sim 90\times$), while also satisfying the accuracy ($\sim$92%) and power constraints ($\sim$3 W). The proposed architecture was implemented on a Spartan 6 FPGA in order to derive synthesis and evaluation results.

This work extends our previously introduced hardware architecture initially presented in [13]. In particular, the extended work explores the effect of different parameters of the architecture, showing the impact of each parameter on the accuracy, performance, area overhead, and power consumption of the complete system. The architecture presented in this paper further details the novel hardware optimizations that we introduced in [13], in an attempt to make the algorithm hardware-friendly while achieving an effective trade-off between processing performance, accuracy and hardware power overheads. Additionally, a pre-processing step has been added to the proposed hardware architecture in an attempt to improve the overall accuracy of the vessel segmentation process while satisfying the constraints of a portable system.

The rest of this paper is organized as follows: In Section 2 we present background information on retinal vessel segmentation and the software-based algorithm used for the retina blood vessel extraction in the proposed approach. Section 3 provides details on related work. Section 4 describes the proposed system architecture. Section 5, presents the experimental platform and implementation results, and finally, Section 6 concludes the paper and discusses future work.

2. Background

2.1. Retinal vessel segmentation

The retinal vasculature is composed of arteries and veins that appear as elongated features, with their branches visible within the retinal image Fig. 1. Typical vessel width ranges from one to twenty pixels depending on the image resolution and the width of the vessel. Retinal images also contain other structures such as the optic disc, the retina boundary, and in the case of different diseases exudates and wool spots.

The blood vessel tree is an important anatomical structure in the human retina. Various diseases, such as diabetic retinopathy, cause damages and several abnormalities to the structure of the vessels. Automatic detection and segmentation of the retina vessel tree helps physicians to diagnose and monitor these various diseases [14]. Another significant use of the retina is in identification; the blood vessels pattern of the retina is unique, and even the eyes of the same person have a different structure [15]. Because of the internal location within the eye, the retina is not exposed to the external environment and thus is a very stable biometric [16].

There exists a large number of algorithms in literature that focuses on the segmentation of the retinal blood vessels, and can be classified into two broad categories: supervised and unsupervised. Furthermore, retinal vessel segmentation algorithms are divided into seven main categories as mentioned in [6]: (1) pattern recognition techniques, (2) matched filtering (MF), (3) vessel taking/tracing, (4) mathematical morphology, (5) multi-scale approaches, (6) model based approaches and (7) parallel/hardware based approaches.

Among the above categories, the method yielding the most accurate results is the matched filter [17]. The proposed architecture is therefore inspired by a matched filter approach as it was initially proposed in [18] and further improved in [12]. This algorithm utilizes matched filtering along with a threshold technique to achieve detection of the blood vessels in retinal images, and enhance the visual segmentation of the blood vessels. The proposed matched filter in [18] was designed for a hardware image processing system and the main advantage of it is that the filter is implemented using integers instead of floating point values which makes the algorithm hardware-friendly.

2.2. The matched filter-based algorithm

The matched filter is a template matching algorithm that is used in the detection of the blood vessels. The matched filter describes the expected appearance of the blood vessels by approximating them using a Gaussian shaped curve and it is designed based on three main properties of the vessels:

- Blood vessel shapes have small curvature so can be approximated antiparallel segments.
- Vessels are observed as darker areas in comparison with the background.
- The width of the vessels lies in the range of 2–10 pixels.
- The intensity profile varies by a small amount from vessel to vessel.

Considering these properties, Chaudhuri et al. [18] proposes a Gaussian function as a model that fits the blood vessels profile. The matched filter kernel may expressed by

$$k(x, y) = -\exp\left(-\frac{x^2}{2\sigma^2}\right) \ \forall |y| \le L/2$$

where L is the length of the vessel segment that has the same orientation and σ defines the spread of the intensity profile. More details about the matched filter can be found in [18].

In addition, the model is extended into two dimensions by assuming that the vessels have fixed width and direction for a short length. Since the vessels may appear in any orientation, the matched filter is rotated in all possible orientations and the maximum response from the filter bank is registered. The resulting kernels are convolved with the retinal image and the matched filter response (MFR) indicates the presence of the vessels.

The MFR is thresholded via a threshold value calculated automatically through iterative thresholding, and selected based on the number of pixels that have the most common pixel value on the image. The outcome of the threshold operation is a binary tree of the blood vessels.

Threshold probing is used next, where the segments created by the thresholding are used to locate a set of starting points to initialize the probe queue. The probing is repeated until the appropriate threshold for the area being probed is determined.

2.3. Preprocessing using Gaussian low pass filtering

The integration of a preprocessing step in image processing algorithms is a very common technique, used in several applications. Preprocessing aims to improve the quality of the image